# The Evolving Role of Automation in Intel® Microprocessor Development and Manufacturing

Kumud M. Srinivasan, Logic Technology Development, Intel Corporation

Index words: automation, 300mm, D1C, information turns, AMHS


## ABSTRACT

In March 2001, Intel completed production of "first silicon" from its 0.13-micron technology, 300mm wafer development fab. Named "D1C," this fab represents the most sophisticated level of automation in Intel today, and an inflection point in the evolution of fab automation within Intel. In this paper, we travel down this path of evolution detailing the role of automation in process development and manufacturing.


## INTRODUCTION

This paper describes the pervasive role that automation is playing in 300mm process development and manufacturing. This is contrasted with the role that automation has played in Intel's 150mm and 200mm process development and manufacturing. Additionally, we outline some of the future challenges and opportunities in this area.

Many aspects of this automation evolution are explored. We describe automation's changing role from a support function, to a technology module, to an enabler of 300mm operations. We characterize the role of automation in "information turns" and discuss its ability to speed up the process development cycle time. A view of the increasing richness of capabilities, the re-use profile, and the improvement in reliability and availability over technology generations is also given.

## AUTOMATION IN PROCESS DEVELOPMENT AND MANUFACTURING

### Automation and Information Turns

Why is automation important? During process development, quick information turnaround is required to hit process targets and to sustain the ever-increasing speed of process technology conversions. From Figure 1 below, we can see that quick information turnaround means increasing information and WIP turns. (WIP turns are defined as the number of wafers processed through an activity in twenty-four hours, divided by the total wafer inventory.) The goal during the experiment-execution phase, or the manufacturing phase, is to increase WIP turns. An increase in WIP turns automatically increases information turns. Additionally, information turns are impacted by the cycle time of information during the experiment-design phase as well as by the time it takes to analyze data after a lot leaves the fab.

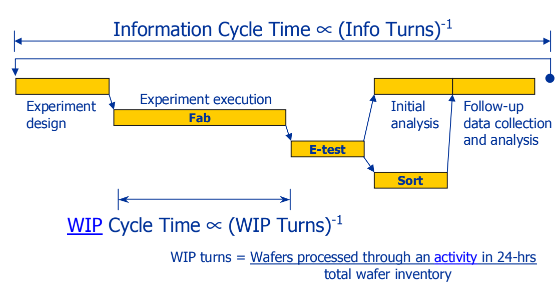


**Figure 1: Information turns and WIP turns**

Automation systems can speed up information turns in many ways. As Figure 2 shows, experiment definition systems help design and specify experiments. Manufacturing execution systems enable experiment definition and execution and overall work flow control in the fab. Equipment control systems automate tool control, and wafer handling is automated via material-handling systems. Decision support systems help monitor fab performance. Data analysis systems enable analysis of E-test, yield, and Sort data. The challenge of automation systems, then, is to enable, via these systems, ever-increasing information and WIP turns.

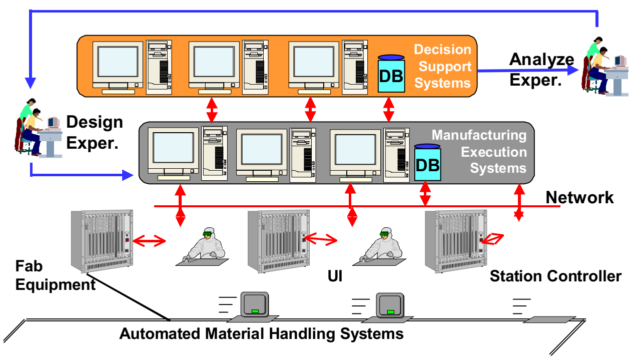


**Figure 2: Automation in process development and manufacturing**

### Automation as an Enabler of 300mm Operations

With 300mm technology, the role of automation has taken on even more significance. We now have much larger wafers, about 12 inches in diameter, which is more than twice the surface area of 200mm wafers, which are about eight inches in diameter. These wafers provide 240 percent more area for printed die per wafer than standard 200mm wafers, thereby lowering production cost per chip. This increase in the size and weight of wafers has created new challenges for automation systems.

Ergonomic challenges caused by the increased size and weight of wafers have resulted in the need for automation of all wafer handling, and in the emergence of automation systems to transport wafers directly to and from each tool in the factory. Today, Intel's 300mm fab, D1C, features the world's first fully automated system for handling wafers. Tools with mini-environments and slot selection capabilities enable wafer handling to be completely automated: stockers and carousels store wafers; a monorail, overhead vehicles, and automated guided vehicles transport wafers to and from tools and stockers. Contrast this with a typical 200mm fab where WIP racks are used in conjunction with stockers to store wafers, WIP carts are used in conjunction with interbay systems to transport wafers, and wands are used for wafer handling. The high level of mechanical automation in the 300mm fab is accompanied by a tight integration of data automation systems–equipment control, scheduling and manufacturing systems–resulting in the ability of 300mm fabs to progress from basic point-to-point delivery of wafers to continuous, uninterrupted processing, and eventually to lights-out operations.

The pervasive automation of wafer handling has enabled the movement of wafer processing away from the bay to a central location in the chase, or to a command center, which makes for a safer environment as it reduces human contact with material-handling systems. In 200mm fabs, technicians run tools from the front in bays. The automation in the 300mm fabs enhances productivity as it enables one technician to run several tools from a single location. It enables dense packing of tools with fewer tool interfaces thus supporting changes in the design of user interfaces and workstations. The user interface is evolving from one that is designed to be highly interactive with the technician to one that facilitates the remote management of clusters of tools. Likewise, workstations are being designed to support mobility via wireless devices and tool operations via command centers.

The use of test wafers represents yet another operational change in 300mm fabs. The higher cost of wafers has resulted in the need for their extensive re-use through regeneration and reclaim. The inability to manually handle wafers has resulted in the need for extensive tracking of wafers at the wafer level. The pervasive use of automated intrabay systems has resulted in the need for systems that comprehend complex workflows where a tool is held "down" while test wafers are pre- and post-measured. Equipment control and manufacturing execution systems are being extended to address these challenges.

Figure 3 shows the presence and impact of automation systems in a typical 300mm bay-chase.

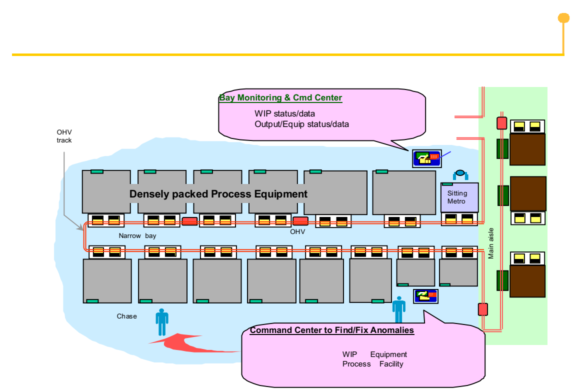


**Figure 3: Automation in the 300mm clean room**

## KEY COMPONENTS AND ARCHITECTURE

So, what is meant by *automation*? As shown in Figure 4, automation components typically belong to one of five primary systems: process equipment interface, manufacturing execution, automated material handling, engineering analysis, and infrastructure (a pervasive layer of hardware, networks, and user interfaces).

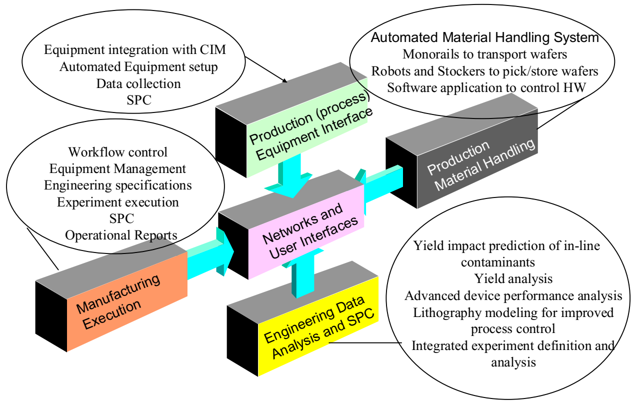


**Figure 4: Key components of automation**

These systems integrate and interact with each other via the use of industry standards, wherever possible, and through custom adapters, where no standards exist. Figures 5 and 6 show two views of the integration architecture as it is implemented in D1C today.

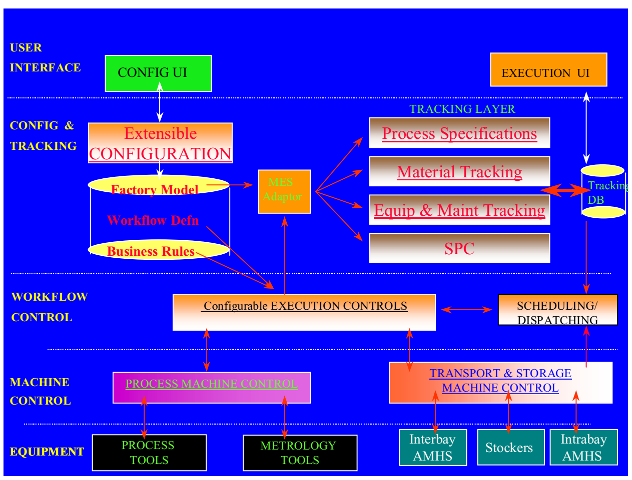


**Figure 5: Automation systems integration architecture**

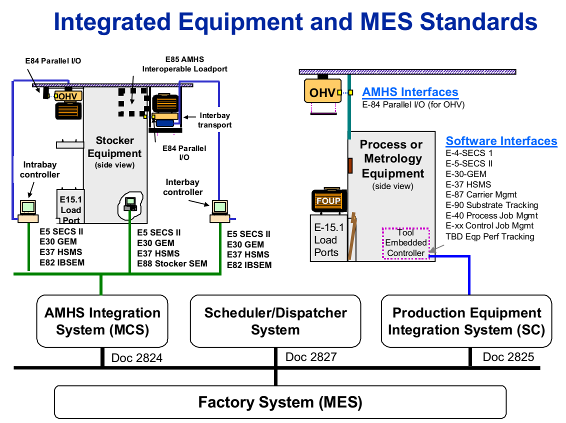


**Figure 6: Use of standards in systems integration**

# INTEGRATION WITH PROCESS TECHNOLOGY

## Automation Technology Cycle

As automated systems have become more complex, so have the inherent methodologies and processes. Process development has, over several technology generations, developed a rigorous methodology and lifecycle as described in Figure 7. The key philosophy behind this methodology is as follows: as a process generation moves from research through development into manufacturing, the willingness to take risks diminishes rapidly because the costs of making mistakes increases dramatically. Because of this, the technical focus changes from evaluation during research to integration followed by replication during the manufacturing ramp. Likewise, management's focus changes from planning to synchronization to control.

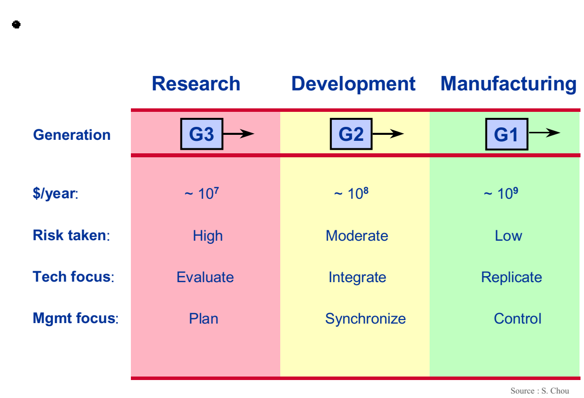


**Figure 7: Technology life cycle**

Automation today has adopted a methodology and lifecycle similar to that of process development. In

150mm and early 200mm technology generations, automation systems were introduced when they were ready, not in a manner that was necessarily synchronous with the process development cycle. The 0.18-micron technology saw the emergence of automation as a technology module, and the adoption of a methodology for managing innovation and risk that mirrored the one that had been successfully used for process development. This resulted in the establishment of an Automation Module Target Spec for a process technology generation. The spec captured automation capabilities to be transferred with a process to high-volume manufacturing sites. The spec established performance and reliability targets for automation systems. Also adopted was the re-use methodology that is used to quantify the extent of change in process equipment from one generation to another. Development of systems was managed by a program as is done for process. A milestone was defined for development completion and integration known as an Automation Baseline. This was pegged at a year prior to ramp start to enable sufficient time for systems to harden for ramp. Transfer and training of personnel at receiving sites were facilitated by adoption of the "seeds" program. This enabled receiving sites to send personnel to the technology development site for training assignments of 6-12 months duration. This technology cycle is captured in Figure 8.

As mentioned previously, 0.18um was the first technology generation in which automation adopted a cycle that mirrored the one used in process. Since then, this methodology has been used successfully in two subsequent generations, 0.13um in 200mm and in 300mm. This has now become the *de facto* standard.

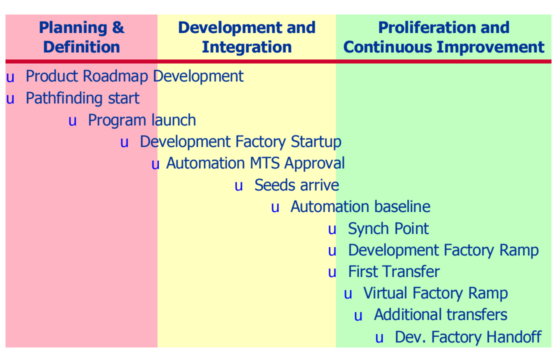


**Figure 8: Automation technology cycle**

## Management Structure and Development Methodology

As expected, the automation management structure has also evolved to accommodate the technology cycle described in the previous section. Figure 9 describes this structure. Basically, the structure and ownership change as the cycle moves through the phases of research, selection, development, and proliferation, enabling the technology during each phase to get an appropriate level of management focus.

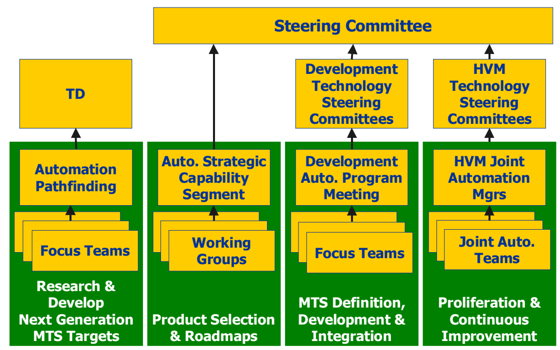


**Figure 9: Management structure**

We now move on to the development and implementation methodology used today, as shown in Figures 10 and 11. The pervasiveness of automation systems in the fabs today has necessitated a high level of rigor in development and implementation methodology. This is because, typically, when an automation system is down, fab processing is halted, and potential revenue is lost.

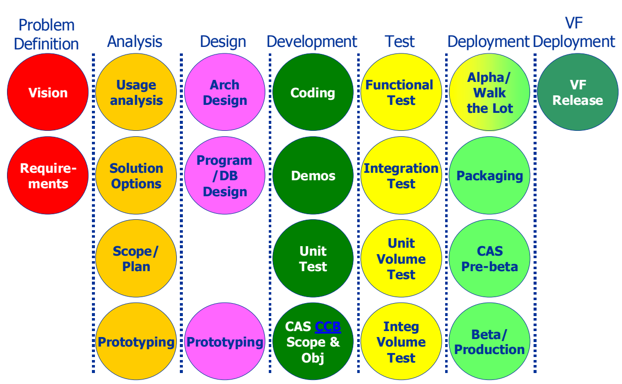


**Figure 10: Development methodology**

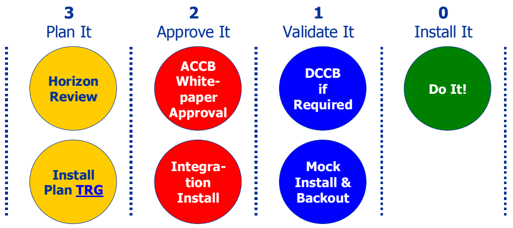


**Figure 11: Automation change methodology**

The impact of the technology cycle, management structure, and rigorous methodologies is evident today in the reliability of automation systems. Reliability has improved dramatically from a mere five days between unscheduled full fab downs in the 0.35um generation to a record 253 days in the 0.13 generation!

## THE EVOLUTION OF INTEL'S FIRST 300MM FAB

Let us now take a look at the evolution of automation capabilities over process generations and see how they have come a long way from the days of the 150mm generation. Figure 11 illustrates this evolution. Incremental capabilities can be seen in all components: equipment control, manufacturing execution systems, material-handling systems, data analysis systems, and system infrastructure and architecture.

| | Equipment Interface | Manufacturing Execution | AMHS | Engineering Analysis |
|---|---|---|---|---|
| 0.8um (6") | DOS-based Eqp Control | Experiment tracking | Interbay | Centralized file management system |
| 0.6um (8") | Unix-based eqp control | Skip lot sampling | Diffusion Intrabay | |
| 0.4um | Statistical process control | | | |
| 0.25um | Excursion Protection | | Litho Intrabay | |
| 0.18um | Stand-alone User Interface, Advance Process Control | Rich Specs | Scheduler | Yield Analysis System |
| 0.13um | | Experiment definition, Cu segregation | | |
| 0.13um (12") | NT-based eqp control, user interface for tool clusters | Test wafer tracking, FOUP management | Pervasive Intrabay | MES-insulated DSS |

**Figure 12: Evolution of automation capabilities**

Equipment interfaces have evolved from DOS-based controllers to NT*-based ones in today's D1C. Along the way, the capability set has expanded from recipe control and data collection to excursion protection and advanced process control. The architecture has evolved from one that had the user interface hard-wired into it to one that is able to handle the user interface as a separate layer. Manufacturing execution systems have given fabs the ability to define and track complex experiments, FOUPs, and test wafers, as well as the ability to view rich specs and the controls to support copper segregation. Material-handling systems have expanded from intrabay in Diffusion and Lithography only to one that is pervasive, and integrated with a fab-wide scheduler. Decision support systems have made significant headway in yield analysis and in architectural insulation from manufacturing execution systems. Through these generations, the architecture has evolved from a single monolithic system to a multi-layered system with a powerful middleware layer: it has gone from dumb terminals to wireless PCs in the clean rooms. Additionally, the technology applied has evolved from DOS to NT, from COBOL to Java* and C++, and from hierarchical to OO databases.

D1C, Intel's first 300mm fab, represents the most sophisticated level of automation in Intel today. It has seen a step-level increase in automation capability from the previous technology generation. This is best illustrated by the re-use profile since 0.25um. A technology generation typically re-uses 75-85% of the previous generation's automation capabilities, and it sees 10-15% new capabilities. Intel's 300mm, 0.13um generation has re-used only ~55% of the capabilities of the equivalent 200mm generation, while it has seen ~50% new capabilities. A look at capital investment shows a similar story: re-use of capital investment has been a mere 25%, with ~100% new investment.

The D1C changes are pervasive, and they cover many components from state-of-the-art decision support system with data warehouse, data mart and OLAP technologies, to sophisticated and tightly integrated scheduling and control systems. But, the highlight is the automated material-handling system. Figures 13 and 14 show examples of some of the material-handling systems in use in D1C today.

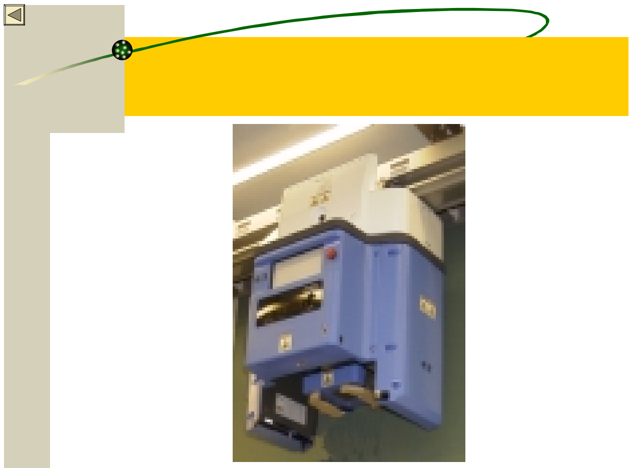

**Figure 13: Overhead vehicle**

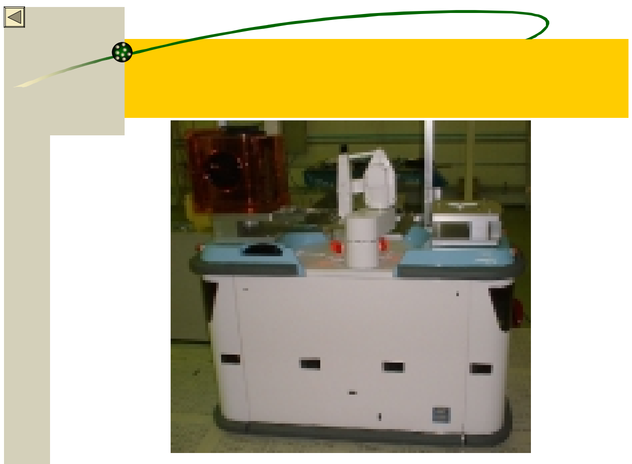

**Figure 14: Automated guided vehicle**

## CHALLENGES AHEAD

As we look ahead, we see some primary trends. As process margins shrink, automation capabilities required to enable new process technologies are increasing. Wafer size increases have significantly increased the demand for full automation across the fab. Moreover, computing technology and available power continue to grow at a rapid pace.

Given these trends, one of our primary challenges is to obtain a fundamental understanding of technology development and manufacturing operations across Fab, Sort, Assembly, and Test to ensure we bring the right solutions at the right time. We need to increase our technical expertise in, and stay current with, computing technologies. We need to become effective system architects and integrators. We need to demonstrate a consistent use of effective development methodologies. And last but not least, we need to maintain our focus on operational excellence.

There are many examples of real opportunities ahead. One is the replacement of the 0.13um manufacturing execution system with a next-generation system that is capable of tracking workflow at a wafer level. Other examples are improvement in storage management (prioritized storage), improved integration with lot sorter tools, and automation of remaining manual areas. More sophisticated equipment control, pervasive advanced process control, remote factory operations, and increased automation reliability requirements are yet other examples of future opportunities.

## CONCLUSION

Factory automation at Intel is at an inflection point. The performance of the 300mm fab of the future will be intricately linked with the performance of its automation systems. This makes it an appropriate time to pause to reflect on the path that automation has traveled and the role that it has played in Intel's microprocessor development and manufacturing. It helps prepare us for the many exciting challenges ahead. And, last but not least, it has made me appreciate the opportunity that I have enjoyed in my years at Intel, the opportunity to influence the direction that automation has taken and to contribute to its rich history.

## ACKNOWLEDGMENTS

I want to thank Sunit Rikhi, my partner and co-manager of LTD Automation, who helped me select the topic for this paper. In addition, many thanks go to the contributors to the "Introduction to LTD Automation" class: Wayne Carriker, Ross Giddings, Hazem Hajj, Kris Hegg, Chandra Mouli, Sunit Rikhi, and Sara Runnings. Much of the information in this paper has been taken from the class materials. Special thanks to Wayne Carriker for the invaluable shots of D1C's AMHS. Last, but not least, thanks to Arnie Sparnins for his input on the role of industry standards.

## REFERENCES

[1] "Introduction to LTD Automation" class. Contributors include: W. Carriker, R. Giddings, H. Hajj, K. Hegg, C. Mouli, S. Rikhi, S. Runnings, and K. Srinivasan.

[2] Carriker, Wayne, "D1C AMHS Status," *LTD Automation Communications Meeting*, August 18, 2000.

[3] Mouli, Chandra and Byrd, Tom, "MES Model," Px60 Ops. Review, WW10.

## AUTHOR'S BIOGRAPHY

**Kumud Srinivasan** is the manager of Logic Technology Development automation in the Technology and Manufacturing Group. She shares responsibility with Sunit Rikhi for managing the development and integration of automation for technology development and manufacturing. Srinivasan joined Intel in 1987 in the Technology and Manufacturing Group's second high-volume manufacturing fab in Albuquerque, where she developed, and later managed, several key automation initiatives and teams. In 1991, she joined the Intel Mask Operation group, and later, Intel Test Tooling Operation group, as manager of software and business development. In 1995, she joined the Portland Technology Development Group. Currently, her scope includes wafer processing and wafer sort and test automation. Srinivasan graduated in 1984 with an M.S. degree from Syracuse University, School of Information Studies, and did a post-graduate stint at UC, Berkeley. In 1981, she received a B.S. degree in Economics from Calcutta University, India. Her e-mail is kumud.srinivasan@intel.com